Validated High Speed Pull and Shear Test Methodologies to Evaluate Pb-Free BGA Mechanical Strength

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Abstract

The conversion to lead free Ball Grid Array (BGA) packages has raised several new assembly and reliability issues. Lead-free solder joints are generally stiffer than tin-lead solder joints, and mechanically induced failures have become more prevalent in lead-free solder assemblies. Traditionally, assembly bend and shock testing is performed to evaluate mechanical assembly reliability. However, bend and shock tests are expensive, cumbersome and not feasible for evaluating lot-to-lot variations in mechanical strength.

Consequently, there is a need for a validated, component level test method that can be used as an accurate indicator of assembly level mechanical strength. Several publications have been written to evaluate the efficacy of high speed pull and shear testing as a viable reliability indicator [1 – 10].

In this study, a comprehensive Gauge R&R study was performed to evaluate the accuracy of the test equipment, including high speed video calibration. Then, test studies were performed to compare the accuracy of the results, spread across different package constructions, solder metallurgies, ball pitch and surface finish. In addition, the effect of parameters like multiple reflows and aging on specific metallurgies and surface finishes was studied. The results were generated over more than 2000 test runs.

Finally, the study rank orders all critical test parameters and articulates what precise steps can be taken to generate relevant data for standard and custom devices during early evaluation stages and during high volume manufacturing.

Keywords

BGA, Pull Strength, Shear Strength, Reliability, Solder Joint, High Speed, Intermetallics, Surface Finish

Introduction

Microelectronic devices are becoming smaller, thinner and more complex. Handheld devices like smart phones are becoming ubiquitous and more complex. Regardless of complexity, consumers expect the same mechanical robustness from them as from older generation products. Moreover, the conversion to Pb-free solders (which are known to be more rigid and brittle than SnPb solders) makes meeting mechanical robustness requirements even more challenging.

In high performance networking products, there are additional challenges. High performance networking assemblies are several orders of magnitude more expensive than consumer handheld assemblies; are expected to last up to 15 years, and are expensive enough that they cannot be discarded if any component in them fails.

Consequently, ensuring mechanical robustness is a primary imperative in both mobile and high performance products. Traditionally, mechanical reliability is evaluated by performing bend and shock testing at test vehicle level and product level on final assemblies. However, these product level tests are baseline reliability evaluation tests as opposed to lot-to-lot screen tests that can ensure consistent mechanical strength in individual products.

It is therefore critical to develop a methodology for evaluating components much before board level assembly, to ensure consistent mechanical robustness. This test method needs to be such that it can be easily implemented in production, and can be used for at least relative comparisons for in-line quality screening. The test method also needs to be sensitive to the critical parameters known to impact mechanical strength: solder metallurgy, surface finish, and assembly conditions.

Several test methods have been proposed in the literature to achieve these objectives, most notably high speed solder pull tests, shear tests and impact (Charpy) tests [1 – 10]. While some amount of correlation and trend analysis has been published on these tests, testing across a broad range of parameters and parts has not been reported, along with the specific parameters that should be used on any one test to ensure consistent results that can help develop an acceptance threshold for mechanical robustness on a lot-to-lot basis.

In this study, a detailed analysis of high speed pull and shear tests is presented, along with trade-offs and optimal parameters for testing samples to compare critical design parameters.

Gauge Repeatability and Reproducibility

Before performing detailed component testing, a calibration was performed on the Dage 4000HS machine, to validate the force and displacement data output by the machine. Separate calibration tests were performed for pull and shear testing.

Pull Testing Machine Verification

A custom set up was developed, to determine force and displacement curves that could be compared with the machine's output. A spring with known spring constant was installed on the machine, to be pulled at specific speeds. The force displacement output of the machine was used to extract the spring constant. The spring constant was then compared with the spring's known constant to estimate the machine's accuracy. One set up challenge was that as the spring was pulled, the force values exceeded the load limit of the machine's force sensor. This was circumvented by using a magnet with predetermined magnetic strength to keep the spring in place. Thus when the force value reached the magnet's force limit, the spring separated from the magnet without exceeding the machine's force sensor limit.

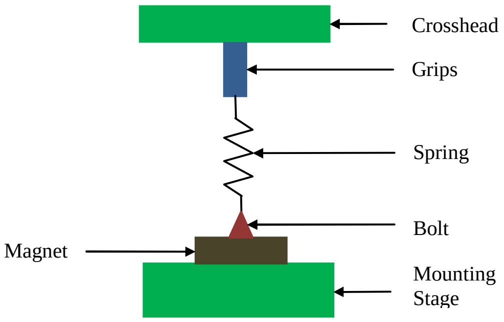

Figure 1: Schematic of Pull Test Verification Setup

A comparison of the spring constants from the machine with that from the spring manufacturer is shown in Table 1.

Test Speed (mm/sec)	Number of Tests Performed	Average Spring Constant (lb/Inch)	% Difference
1	3	19.70	9.44
10	3	18.26	1.44
100	4	18.82	4.56
500	4	18.37	2.06

Table 1: Comparison between Machine and Manufacturer's Spring Constant Values (Pull)

In addition, a high speed camera was simultaneously used to view and record the movement of the spring as it was pulled. A grating pattern was placed behind the spring to translate the displacement rate of the spring into measured speed. The bottom of the grips was tracked as it traveled across certain number of squares (the maximum number visible in the image). The number of squares as well as the number of frames traversed were counted and recorded, to derive the test speed. The speed values from the camera/grating were compared with those recorded by the machine (Table 2). Table 2 shows that the machine reported pulling speed values are quite accurate, up to 400 mm/sec or higher.

Test Number	Pulling Speed from Camera (mm/s)	Pulling Speed from Machine (mm/s)	% Difference
1	205	200	2.56
2	400	400	0.00
3	615	600	2.56
4	633	600	5.56
5	870	1000	13.00

Table 2: Comparison between High Speed Camera and Machine Speed Values

The difference between the high speed video results and the machine output is also likely due to error introduced in the optical measurement by lateral (horizontal) wobbling of the grips during the pull test.

Shear Testing Machine Verification

As with the pull test verification, a custom test fixture was developed to test the machine force-deflection and speed. However, this fixture was more difficult to implement because of the high speeds involved, and the geometry of the set up. Referring to Fig. 2, the machine's shear tool strikes a fulcrum attached to the spring. The resulting spring constants inferred from the force-deflection data of the machine are shown in Table 3.

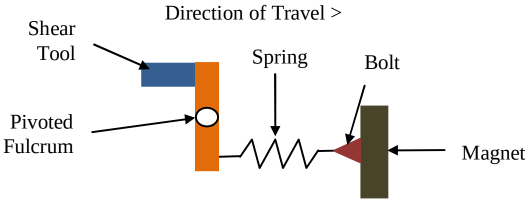

Figure 2: Shear Test Verification Setup (Top View)

Test Number	Test Speed (mm/sec)	Measured Spring Constant (lb/Inch)	Manufact. Spring Constant (lb/Inch)	% Difference
1	10	21.67	18	20.40
2	50	23.17	18	28.75
3	100	22.06	18	22.56
4a	250	22.06	18	22.56
4b	250	24.32	18	35.14

Table 3: Comparison between Machine and Manufacturer's Spring Constant Values (Shear)

The difference in results is higher than in the pull tests. The reason for this is more likely due to the custom verification setup and not the machine. The spread in results from the set up is about 15% for the speeds tested.

As with the pull testing, a high speed camera was also used to verify the test speeds, with a grating pattern. The results (Table 4) indicate correlation to within 8%. Like the pull testing, there is also some error associated with the high speed camera set up.

Test Number	Pulling Speed from Machine (mm/s)	Pulling Speed from Camera (mm/s)	% Difference
1	10	10.00	0.00
2	50	50.00	0.00
3	100	92.31	7.69
4	200	200.00	0.00
5	400	378.95	5.26
6	800	784.61	1.92
7	1000	1020.00	2.00
8	2000	1933.33	3.33
9	4000	4285.71	7.14

Table 4: Comparison between High Speed Camera and Machine Speed Values (Shear)

Overall, the verification results indicate good correlation between the measured and comparison values, particularly for the pull test set up, up to a speed of 400 mm/sec.

Pull Testing

Evaluation Parameters – Learning Cycle 1

After calibrating the machine, a series of preliminary pull tests were performed to compare different package/test parameters on a 1 mm pitch, 35 mm wirebond PBGA. The results of the first learning cycle (Figure 6) showed a dependence on the location of the pull test in the BGA matrix, the speed and the number of cross-bars used.

The force value was higher at higher test speeds; the variation in force values was higher at the package center than at the corner; and the variation in force values was much lower with 2 crossbars as opposed to 1 crossbar. The increased variation was likely due to cantilever bending at the package corners especially if the package was not fully secured with only one crossbar.

Additional results were generated on a smaller, 0.5 mm pitch tape BGA package (Figure 4). The results indicated the same trends: the force values were lower at the corner than at the center of the package, and the force values were higher at higher test speeds. The force values for the 0.5 mm pitch package were about 2.7X lower on average, compared to the 1 mm pitch package. This reduction in force correlated linearly with a reduction in pad area between the two packages. The failure modes between the 1 mm pitch package and the 0.5 mm package are distinctly different. The 1 mm pitch package had brittle fracture, solder fracture, substrate pad cratering and solder extrusions. The 0.5 mm pitch package had only substrate pad cratering and solder extrusions. That was likely because the substrate used in the 0.5 mm pitch package was a 0.5 mm thick polyimide substrate, whereas the 1 mm pitch package had a 1 mm thick BT core substrate. The thinner, softer package substrate rendered it more susceptible to pad craters as opposed to brittle solder joint fracture.

Based on these results, all subsequent tests were performed at 400 mm/s, at the package center, and with at least 2 crossbars placed as close to the pull jaw as possible – on both sides of it.

Aside from these parameters (speed, crossbars and center vs. corner), other parameters were observed to play a significant role in the quality of results: jaw clamping pressure, stage pre-load pressure and jaw hold time before pulling. (The results in Figure 4 also show the effect of jaw clamping pressure). Too low a pressure would result in solder extrusions, while too high a pressure could deform the ball so much that the solder separation close the pad may occur. The ideal clamping pressure is a function of ball size and requires trial and error: gradually increasing the pressure until solder extrusions no longer occur. Typically, the jaw clamping pressure is around 40 psi, while pressures below 20 psi would be too low. These observations are consistent with the literature [2 – 5]. The pre-load pressure depends on the package size/weight and needs to be adjusted by trial and error.

The jaw hold time is critical because the delay allows the deformation of the solder ball to reach steady state and stabilize before it is pulled. If it is pulled immediately after the ball is clasped, the ball will deform within the jaw cavity while it is being pulled vertically, altering the pull force. A hold time of 10 – 30 seconds before pulling is generally sufficient.

Design Variable Testing – Learning Cycle 2

Having established machine calibration and baseline test parameters, additional tests were performed on a broad spectrum of test samples (Figure 7). At least 10 solder balls were pulled per sample, and at least 2 samples were tested per split. All pull testing was performed at the center of the package, using 2 crossbars on each side of the pull jaws. In this testing, the pull speed was kept at 400 mm/sec. Several trends and correlations can be observed from Figure 3:

Effect of Package Type:

The predominant failure modes were mode 1 (brittle fracture), mode 4 (substrate pad crater) and mode 5 (solder extrusion). There was one case of a mixed mode failure (mode 3), where significant solder was left on the pad. Representative pictures of Modes 1, 4 and 5 are shown in Figure 5.

Difference between Package Substrate and PCB Strength:

The PCB sample had the lowest mechanical strength, failing with mode 4 (cratering). This indicates that in apples-to-apples comparisons, the PCB has a lower mechanical strength than the solder joint or the package substrate. This is consistent with what has been observed in board level bend/shock testing, where PCB pad cratering is the dominant failure mode. This is why a separate effort has been dedicated to the characterization of PCB materials [11 – 13].

Effect of Aging:

The package sample with the lowest force was the "O_TC1000" sample. This is a FCBGA package that has been subjected to 1000 cycles of temperature cycling (-55 – 125°C) before testing. Compared with the package that was not subjected to any temperature cycling (O-2), there is a 40% reduction in force. The lower end of the "O_TC1000" force values were slightly lower than the PCB values, indicating that the chances of brittle fracture with aged samples are equal to or slightly higher than the chances of pad cratering. The "O-HTS1000" sample also exhibited a reduction in mechanical strength (~20%), but it was not as significant as that from the 1000 temperature cycles.

In addition, some of the 0.5 mm pitch T-BGA samples were aged at 100°C, 672 hours and re-tested (Figure 8). The results show that the aged samples had a slight reduction in force, but it was not statistically significant. The failure mode changed from pad cratering to brittle fracture with some solder left on the pad. This could likely be due to an increase in IMC thickness due to aging. Consequently, both force/energy to failure and failure mode should be tracked in testing.

Effect of Surface Finish:

In comparing force results across surface finishes, there appears to be some variation with the other factors, but in general, for brittle solder fracture (mode 1), ENEPIG > Immersion Sn > SOP > Electrolytic NiAu. There were no clear trends observed for modes 4 and 5, which is expected because surface finish is not expected to play a significant role in propensity for pad cratering or solder extrusion. However, it is important to note that this trend does not mean that this is the same rank ordering in board level bend/shock testing. In assembly level testing, several other factors play a role, and the weakest link may shift from the package side IMC to some other location.

Effect of Solder Metallurgy:

Comparing across the same surface finish (Immersion Sn), the effect of solder metallurgy (SAC305, SAC105, SAC405) doesn't appear to be significant. This is contrary to observations made in assembly level bend/shock testing, where significant improvements have been reported with SAC105 versus SAC305. The reason for this disparity likely originates from the set up of the ball pull test. If the gripping jaws are placed very close to the base of the ball, the bulk of the ball is encased in the jaw when it is pulled. Consequently, bulk stiffness effects of the ball are overshadowed in the test, so the effects of solder metallurgy within Pb-free solders cannot be extracted from this test, contrary to some of the observations in the literature [7].

However, the secondary effects of solder metallurgy can be captured by the test method as follows: the choice of solder metallurgy can impact the type/thickness of IMC formed at the solder/pad interface. The pull test can capture the impact of the IMC, but not the impact of the bulk solder metallurgy. Consequently, care should be taken in making inferences from pull test data. It is strictly a Solder-IMC interface, IMC-Pad and Pad-Dielectric interface verification test.

Effect of Package Vendor:

The effect of package vendor can be seen in several test splits. There does seem to be a statistically significant difference in mode 1 results obtained from vendors P and L. There is a difference in package size between the two vendors (31 mm vs. 40 mm), but the difference in results is not likely due to package size, since a 2-crossbar set up was used. The differences were more likely due to differences in reflow conditions/processes during ball attach. Differences in reflow conditions can cause differences in IMC thickness, which in turn can impact mechanical strength.

Effect of Test Operator:

Except for one case, where the operator error was identified, the difference in results between two operators was not statistically significant. This indicates that with proper training and control of test parameters, the results can be operator independent. This evaluation is critical in implementing the test method for lot-to-lot screening. From the data, it also appears that with a standard deviation of 100 – 400 grams, a difference in average force value of 1000 grams can be detected with a sample size of 20, at a 95% confidence level.

Design Variable Testing – Learning Cycle 3

Having completed learning cycle 2, a more detailed set of package parameters were selected for learning cycle 3. In this round, the effect of multiple reflows, pitch and package type were also incorporated (Figure 9). As before, several trends can be observed from the pull testing.

Effect of Multiple Reflows:

Some of the samples were subjected to 6X reflow after they were received. When compared with samples that only had 1 reflow (ball attach), the results varied depending on the surface finish. With ENEPIG, the difference in mode 1 results was statistically insignificant. With Electrolytic NiAu, the increased number of reflows resulted in the same average force values, but a higher spread in mode 1 results. Consequently, an increase in variability can be expected from the results with multiple reflows. This also lends credence to the best practice of performing at least 3X reflow on samples before performing board level bend and shock testing.

Effect of Ball Pitch:

As with the evaluation studies, the force values were lower with smaller pitch for the same failure mode. The reduction in force scaled linearly with pad area. In general, the standard deviation with the smaller pitch parts (max 100 grams) was a smaller percentage of the mean pull force value, than in the larger pitch parts. This may be partly because of a higher bending moment experienced by a larger ball, resulting in more mixed load pull forces than the smaller ball. No pure mode 1 failures were observed with the smaller pitch packages. However, a sizeable number of mixed mode (mode 2 and mode 3) failures were observed.

Effect of Solder Metallurgy:

In comparing the effects of different solder metallurgies, it is clear that those samples with SnPb solder had slightly lower pull forces than those with Pb-free solder. However, the reduction was within the standard deviation of the testing, and hence statistically insignificant. In comparing force results of SAC 305, SAC 105 and SnAg, no significant differences in pull force values were observed.

Difference between Pull Force and Energy Metric:

The corresponding energy results of learning cycles 2 and 3 are shown in Figures 7(b) and 9(b). For learning cycle 2, the results are very similar to the force values, and give the same trends. For learning cycle 3, there are some differences in the trends between force and energy. For example, the effect of multiple reflows results in a slightly lower energy value, while the average force value is slightly increased. The difference in force is not statistically significant, but the difference in energy is statistically significant. On the effect of solder metallurgy, there appears to be a statistically insignificant difference in both force and energy. These results indicate that if higher resolution is needed to detect differences within lots, the energy metric can be more effective.

Shear Testing

Evaluation Parameters – Learning Cycle 1

After verifying the machine, a series of preliminary shear tests were performed to compare different package and test parameters. While the shear test is more prevalent because of its ease of testing, it poses several implementation challenges. First, most of the package solder balls need to be removed from the package before testing. The ball removal process can be uncontrolled and ultimately impact the un-removed balls. Secondly, the package needs to be fixtured such that it is fully attached to the test table. This fixturing depends on the package construction. In high speed camera testing, it was observed that the edges of overmolded packages and some FCBGA packages had solder balls extending beyond the mold/lid edge. When these solder balls were sheared, the underlying substrate was bent so much, that the results were significantly altered (Figure 3). These balls should not be used in the testing.

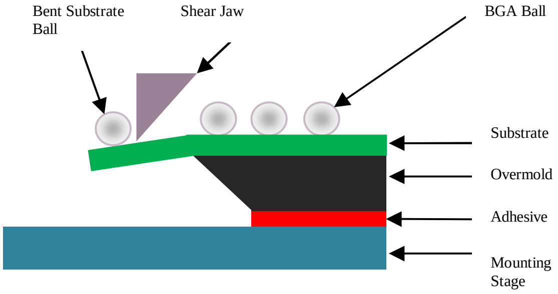

Figure 3: Schematic of Substrate Edge Shear Testing

Using crossbars to hold down the substrate also produced more varied results, unlike the pull test (Figure 10). The effect of the clamp and test location was quite significant. In some FCBGA packages, the lid is only attached to the die (direct-lid-attach). For these packages, it is important to either perform testing at the substrate level only, or design a fixture to prevent flexure of the substrate. The testing was performed at 1000 mm/s.

While gluing the substrate to the mounting stage was also used, the challenge is in ensuring coplanarity of the substrate along its entire length while the jaw/table reach the target speed before impact. The challenges with the package edge are not resolved by gluing the package to the mounting stage.

A fundamental issue with shear testing is that the force applied to the solder ball at impact is not pure shear or pure pull. A bending moment is applied to the solder joint, which produces a complex stress state at the solder/IMC interface. Each test has its tradeoffs: the pull test is a bit more difficult to perform and requires more upfront control of test parameters, but produces more consistent results, while the shear test is easier to perform, but the results have more scatter in them.

Impact (Charpy) Testing

High speed impact testing was also performed on some samples for comparison. The test machine was the Condor 100 from XYZTec. The test parameters used for the impact testing were: 450 mm/s for the 0.5 mm pitch (0.3 mm ball) packages and 360 mm/s for the 1 mm pitch (0.635 mm ball) packages. Two pendulum weights were added for use on the 1 mm pitch samples, to create sufficient energy for impact. The impact speeds were selected after preliminary tests to determine the average speeds at which transition from ductile to brittle occurred. The results are outlined in Figure 11. The trends are similar to those observed in the high speed shear testing:

1. There was a reduction in peak force and energy with ball size/pad size, which scales almost linearly with pad area.
2. The differences in pull force/energy with ball metallurgy were statistically insignificant.
3. The force/energy values from the impact test were at a different order of magnitude from those of the pull and shear tests. The impact test is somewhat similar to the shear test in that the loading conditions applied to the ball are a mixture of peeling and bending.
4. Like the pull and shear tests, it does not appear to discern between solder ball metallurgies.

Conclusions

A comprehensive test vehicle study to understand the mechanical strength of Pb-free BGA solders is presented. Force-displacement and speed characteristics of pull and shear test methods were checked, and several details of the test methods were investigated to derive trends and correlations between critical package parameters. The results demonstrate that at least one of the test methods is capable of repeatably detecting a correlation between mechanical strength and IMC characteristics. The best practices learnt from this study were shared with JEDEC, and most of them have been incorporated in the latest revision of the JEDEC High Speed Ball Pull Test Method (JESD22-B115).

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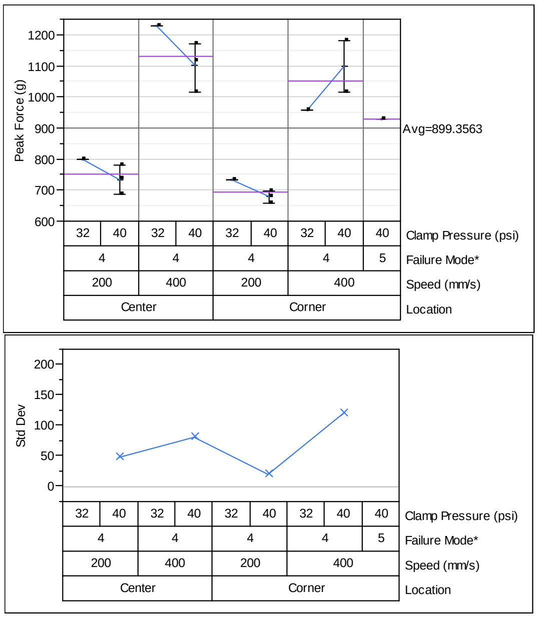
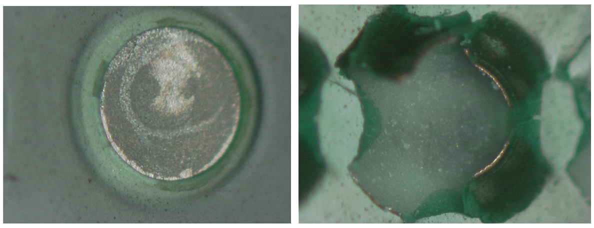
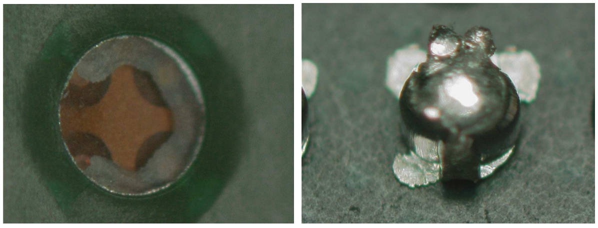


Figure 4: Learning Cycle 1 Force Results: Dependence on Speed, Location and Crossbars (Wirebond 9mm T-BGA, 0.5 mm Pitch)

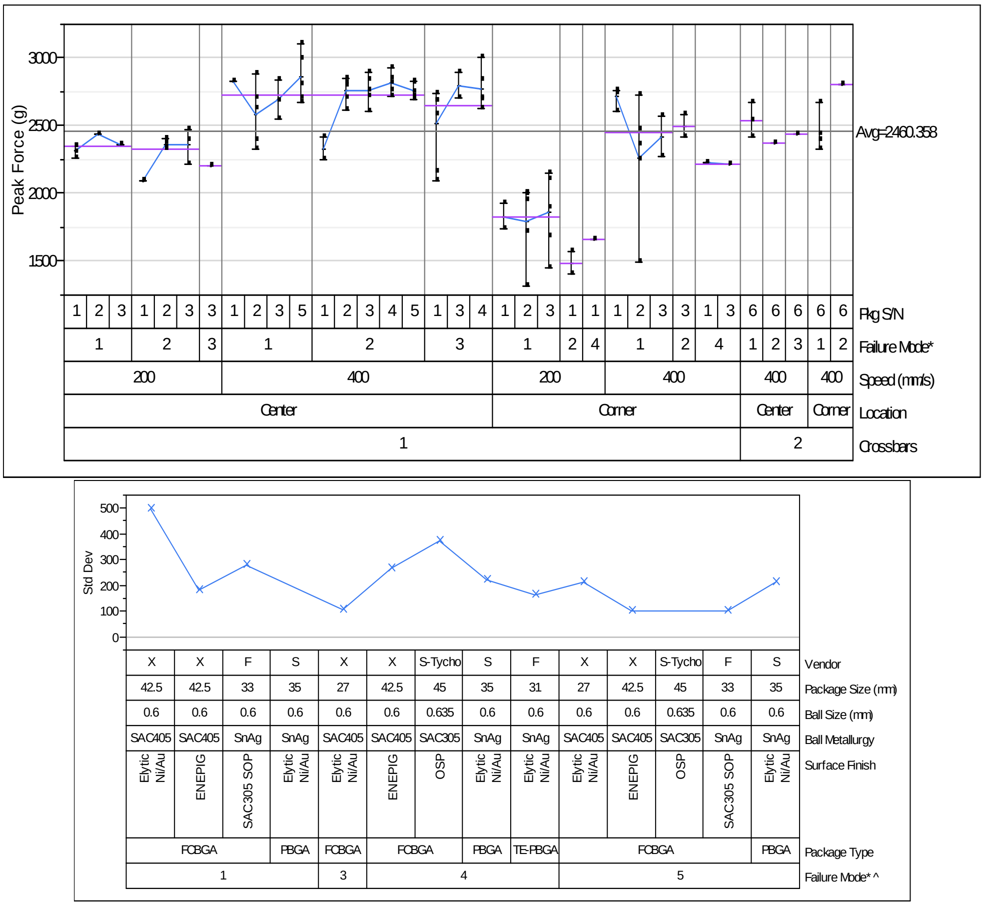


(Mode 1) (Mode 4)



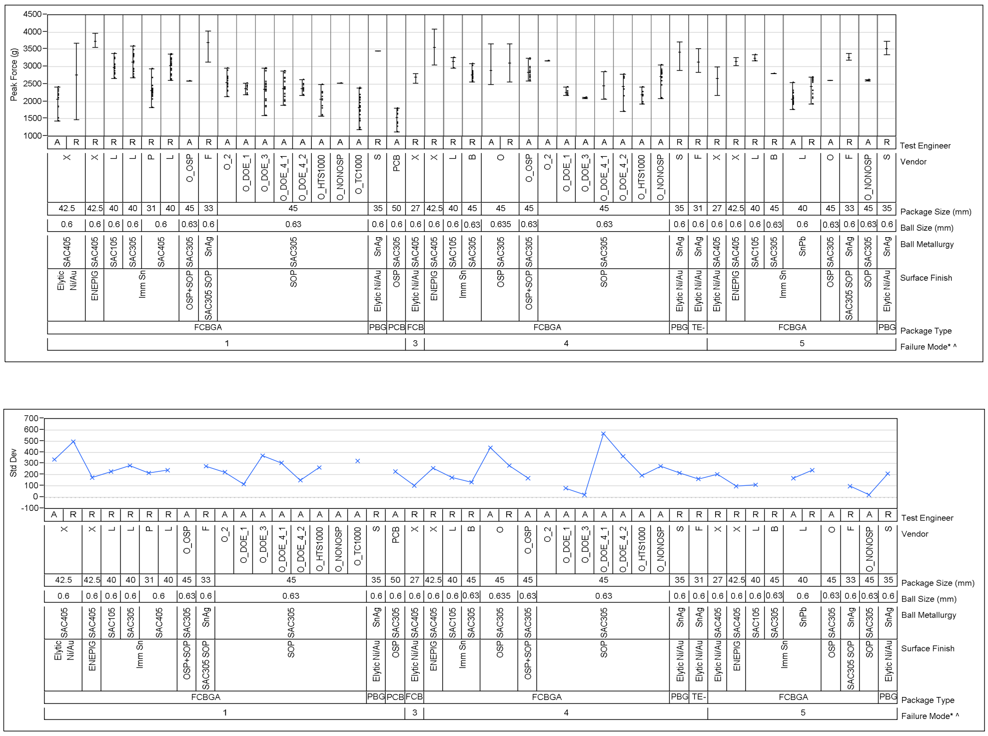
(Mode 4) (Mode 5)

Figure 5: Some of the Failure Modes Observed in Testing



* Mode 1(Complete Brittle Fracture), Mode 2 (Little Solder Left), Mode 3 (Significant Solder Left), Mode 4 (Pad Lift), Mode 5 (Extrusion)

Figure 6: Learning Cycle 1 Force Results: Dependence on Speed, Location and Crossbars (Wirebond 35mm PBGA, 1 mm Pitch)



Cycle Figure 7(a): Learning 2 (Pull) Force Results. All Tests Performed at 400 mm/s

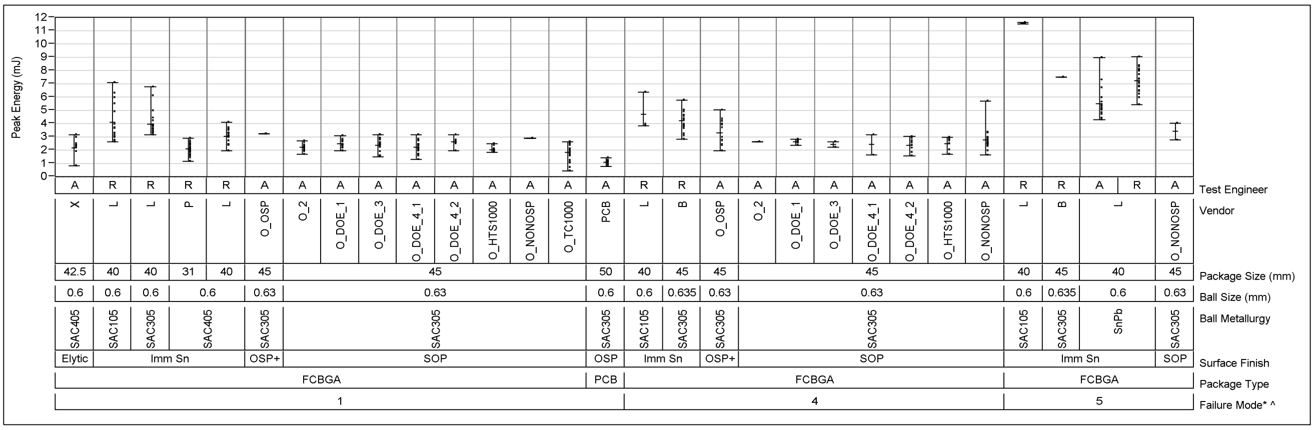


Figure 7(b): Learning Cycle 2 (Pull) Energy Results. All Tests Performed at 400 mm/s

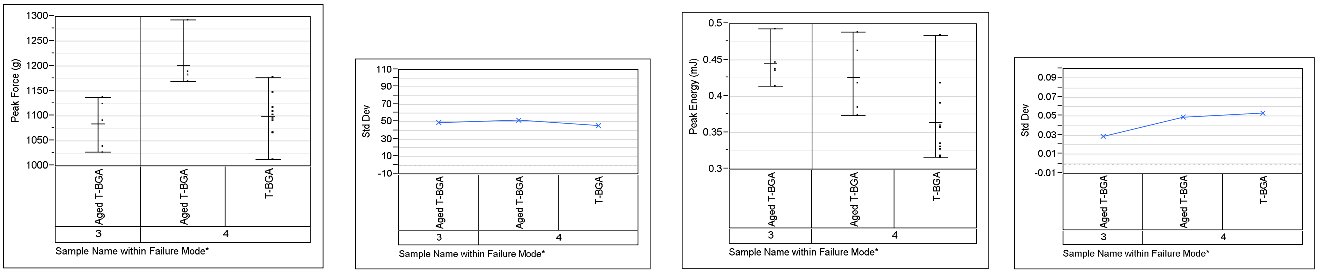


Figure 8: Learning Cycle 2 (Pull) Aging Test Results. All Tests Performed at 400 mm/s

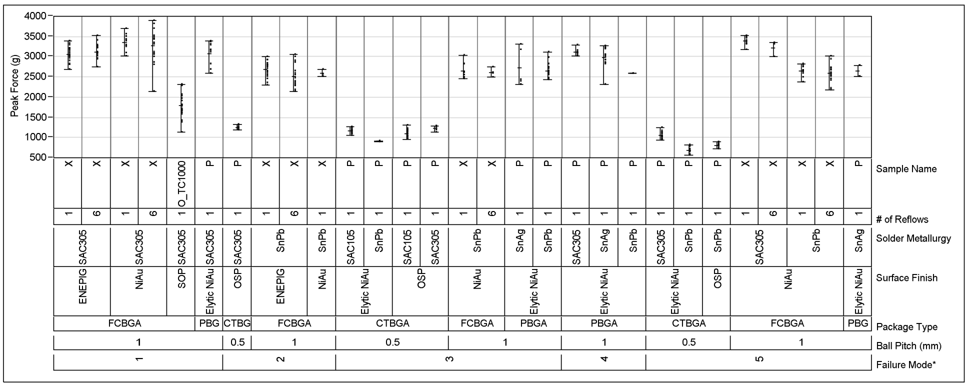
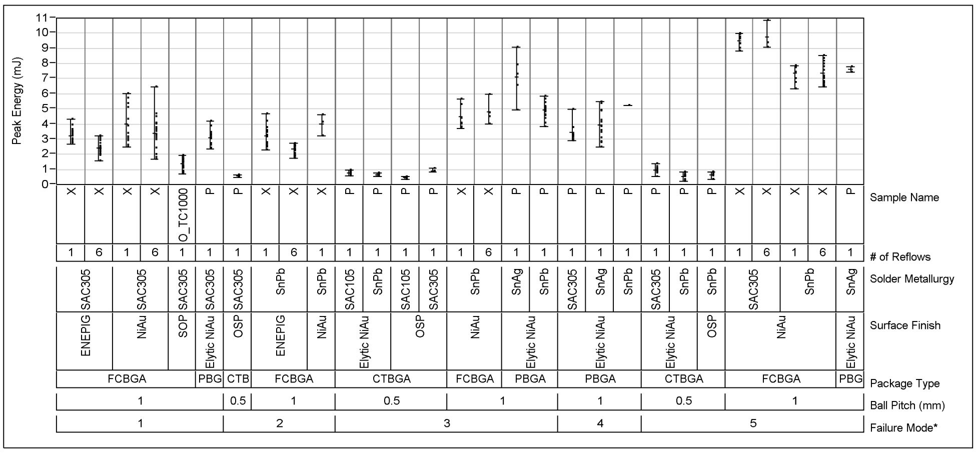


Figure 9(a): Learning Cycle 3 Force Results



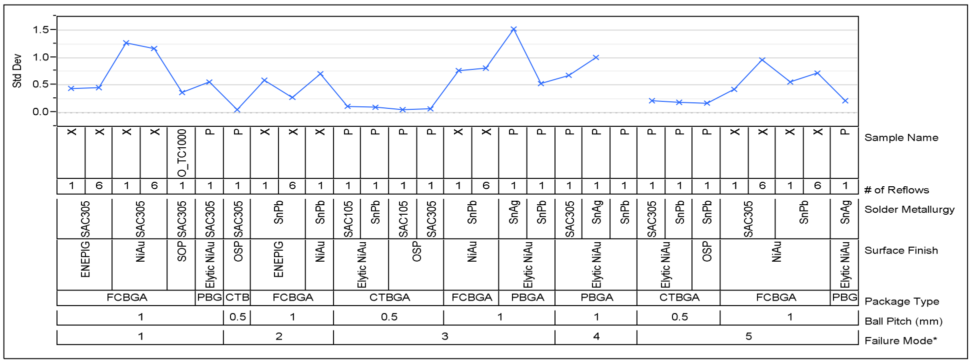


Figure 9(b): Learning Cycle 3 Energy Results

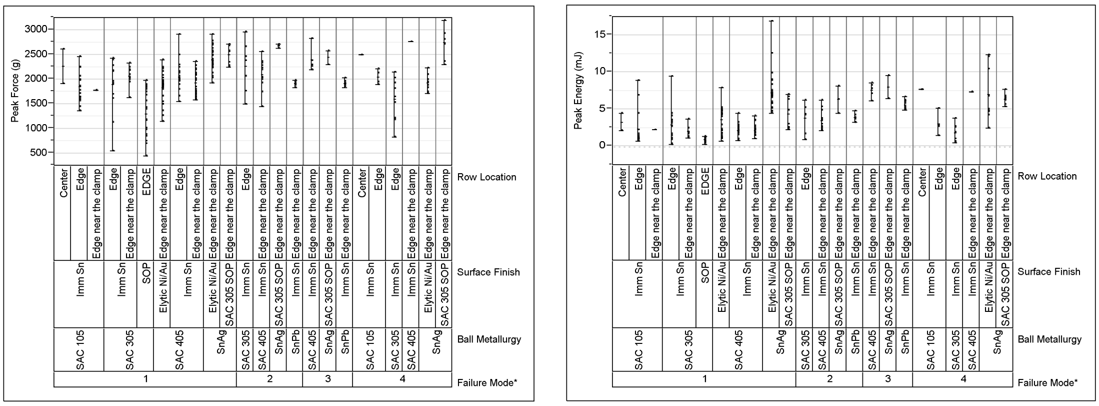


Figure 10: Shear Testing Force and Energy Results

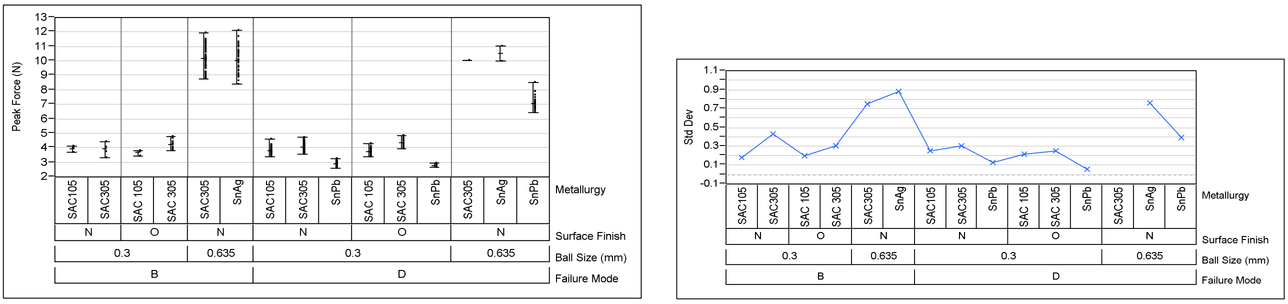


Figure 11(a): Impact Testing Results (Force)

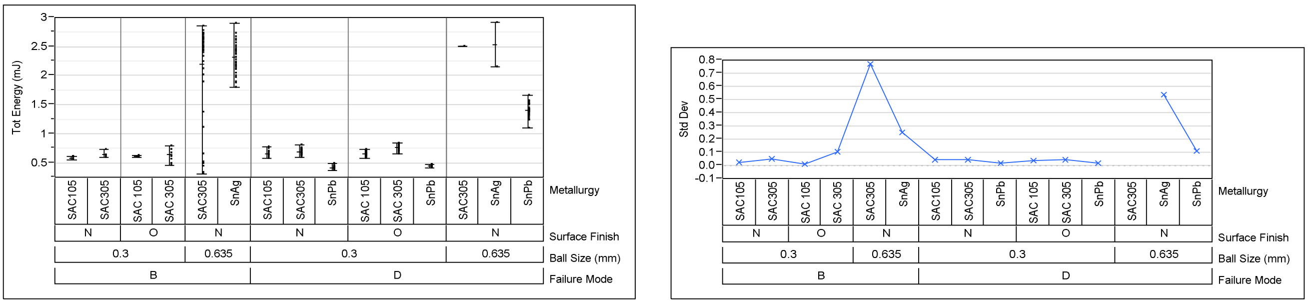


Figure 11(b): Impact Testing Results (Energy)